TOWARDS THE DESIGN OF A LAYER-BASED ADDITIVE MANUFACTURING PROCESS FOR THE REALIZATION OF METAL PARTS OF DESIGNED MESOSTRUCTURE

Christopher B. Williams, Farrokh Mistree, David W. Rosen
The George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
813 Ferst Drive, Atlanta, GA, 30332
404-894-9668, david.rosen@me.gatech.edu

ABSTRACT

Low-density cellular materials, metallic bodies with gaseous voids, are a unique class of materials that have high strength, good energy absorption characteristics, good thermal and acoustic insulation properties, accompanied by an extremely low mass. Unfortunately, current cellular material manufacturing processes severely limit a designer's ability to control the part mesostructure, the material composition, and the part macrostructure.

As such, the authors look towards the use of layer-based additive manufacturing (AM) as a means of providing the design freedom that is currently absent from cellular material manufacturing processes. Since current metal-based AM techniques do not offer an adequate means of satisfying the unique requirements of cellular materials, the authors carry out the conceptual design of a new AM process that is dedicated to the manufacture of cellular materials. Specifically, the authors look to the layer-based additive fabrication of metal oxide powders followed by post-processing in a reducing atmosphere as a means of fabricating three-dimensional, low-density cellular metal parts with designed mesostructure. In this paper, the authors detail this conceptual design process and select working principles that are worthy of further investigation. Insights gained as a result of designing an AM process for a specific class of geometry (e.g. considerations for small wall thickness, high quality surface finish, internal voids, and support material) and investigating the use of AM for production-scale manufacturing are also detailed.

Keywords: Additive Manufacturing, Cellular Materials, Designed Mesostructure

1. MANUFACTURING LOW-DENSITY CELLULAR MATERIALS

Low-density cellular materials are metallic bodies in which any kind of gaseous voids are dispersed. This special class of materials feature a metallic phase that divides space into closed cells (in the range of 0.1 to 10 mm) which contain the gaseous phase, as shown in Figure 1 [1]. The key advantage offered by cellular materials is high strength accompanied by a relatively low mass. The use of such materials also provides good energy absorption characteristics and high compression strengths. Often they provide good thermal and acoustic insulation properties as well. Finally, and maybe most importantly, these materials can be designed and configured in order to effectively support and improve multiple functions of a part (i.e., structural heat-exchangers). Unfortunately, existing cellular material manufacturing techniques constrain a designer to a predetermined part mesostructure, material type, and macrostructure. Such limitations prevent a designer from creating an ideal mesostructure for the (multiple) design goal(s) of the part's intent.

In general, four severe limitations are prevalent throughout cellular material manufacturing processes:

(i) *limited part geometry* – existing techniques are unable to produce cellular structures for any conceivable three-dimensional geometry
(ii) *limited materials* – existing techniques have a limited selection of working materials
(iii) *non-repeatable results* – some processes create cellular structures where voids are distributed randomly; as a result, part quality is not consistent
(iv) *limited mesostructure topology* – most cellular manufacturing techniques either cannot predict the morphology of the pores, or can only consistently produce one certain pore size or shape

These criticisms are related to specific cellular manufacturing techniques in Table 1. From a high level of abstraction, these limitations are representative of the overall lack of designer freedom offered by these different manufacturing techniques.

Table 1. Designer Freedom Offered by Various Cellular Material Production Techniques

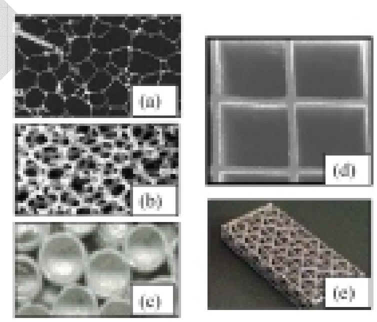
		Processes	*Repeatable*	*Material Freedom*	*Mesostructure Freedom*	*Macrostructure Freedom*
Stochastic	Metal Foams	Hydro / Alcam / Combal		✔		
		Alporas				
		Gasar / Lotus				
		Alulight / Foaminal				✔
		Formgrip				✔
		Metal Sponges		✔		✔
		Hollow Sphere foams	✔			
Ordered		Honeycombs *(via crimping & stamping)*	✔	✔		
		Lattice Block Materials	✔			
Designed Mesostructure		Linear Cellular Alloys *(via extrusion & reduction)*	✔	✔	✔	
		Truss Structures (via Additive Manufacturing)	✔		✔	✔

1.1. Conventional Cellular Material Manufacturing Techniques

Due to the required intricate internal geometry, manufacturing a component with cellular mesostructure is nearly impossible with subtractive machining. As such, researchers have looked to other technologies such as molding, forming, joining, and additive manufacturing. Cellular materials and their processing techniques are classified by the arrangement of the internal voids – stochastic (Fig. 1a-c), ordered (Fig. 1e), or by design (Fig. 1d).

Stochastic materials, having a random distribution of voids, are created by forming gas in liquid metal (Alporas, Hydro/Alcan/Combal, Gasar/Lotus processes), or by mixing metal powders with a blowing agent which is then compacted and melted (Alulight/Foaminal techniques) [3];[4]. Stochastic cellular materials "are inexpensive but place material in locations where it contributes little to material properties (other than density)" [5]. Stochastic techniques do not provide repeatable, predictable results. The techniques limit a designer in the types of macrostructure that can be made. Typically, only aluminum and aluminum alloys can be used due to processing constraints (hydrogen gas used to foam the melt embrittles many metals) [6]. Furthermore, the processes are difficult to control and improve through process optimization [1].

Ordered cellular materials are characterized by a periodic unit cell or by a repeating structure throughout the part. These structures have superior mechanical properties, including energy absorption, strength, and stiffness [7], as well as lower pressure drop and high surface area densities than stochastic metal cellular structures – important properties for heat transfer performance [3]. Ordered cellular materials can be made by stamping or crimping thin sheets of metal into a corrugated shape and then joining them to create ordered cellular structures [8]. They can also be processed by sand casting specially made preforms to create truss structures [9]. Although they offer repeatable part quality, the techniques constrain a designer into the use of a specific mesostructure, and into planar macrostructure.



LOW-DENSITY CELLULAR MATERIALS

Stochastic
- (Solid) metal foams **(a)**
- Metal sponges **(b)**
- Porous metals
- Hollow sphere foams **(c)**

Ordered
- Honeycomb (via crimping & stamping)
- Lattice Block Materials **(e)**

Designed Mesostructure
- Honeycomb **(d)** (via direct reduction; aka Linear Cellular Alloys)
- Truss Structures (via Layer-Based Additive Manufacturing)

Figure 1. Low Density Cellular Material Mesostructure [2] and Classification

1.2. Cellular Materials with Designed Mesostructure

The most limiting constraint of the processes reviewed in Section 1.1 is their incapability to create unlimited mesostructure topologies. If the key benefit of using cellular materials is increased part strength while minimizing mass (or another comparable set of performance parameters), a designer will want complete control over the placement of the material, and/or the determination of the proper mesostructure for the specific product intent. In order to emphasize the desire for freedom in cellular materials manufacture, a separate classification of cellular materials is presented in Figure 1. Cellular materials with *designed mesostructure* are a class of cellular structures wherein material is strategically placed in order to achieve the part's (multiple) design objective(s) (i.e., low mass, high strength, high stiffness, etc.).

1.2.1. *Linear Cellular Alloys via Reduction*

In order to alleviate the existing limitations and processing difficulties, the Georgia Tech Lightweight Structure's group has looked toward the extrusion of specialized ceramic pastes to create linear cellular honeycombs. The process (illustrated in Figure 2) begins with a metal oxide-based ceramic paste (containing lubricants, binders, and other additives) that is extruded through an interchangeable die. The ceramic green body is then dried, and processed in a reducing atmosphere to chemically convert the precursor into a metallic artifact [10].

With this technique, Cochran and coauthors have successfully processed a number of transition metal oxides (Fe, Ni, Co, Cr, N Cu, Mo, W, Mn, and Nb), as well as many engineering alloys including stainless steel, maraging steel, Inconel, and Super Invar [2]. Furthermore, no other lightweight structure manufacturing approach demonstrates comparable values in properties [11].

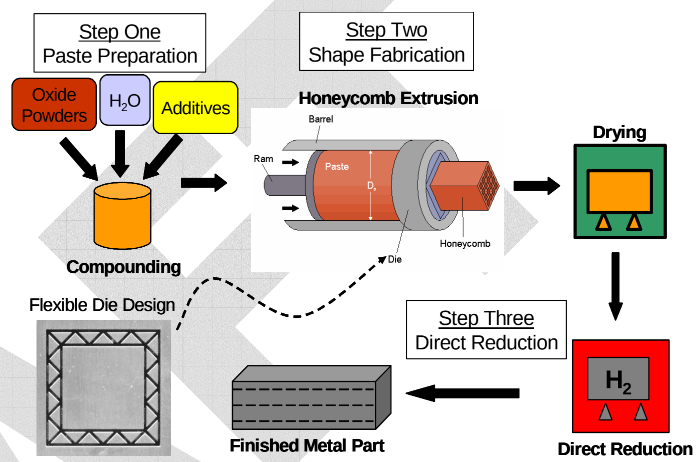


Figure 2. Linear Cellular Alloy Manufacturing Process [11]

With the LCA manufacturing process it is feasible to fabricate honeycomb structures with cell sizes in the range of 0.5 to 2.0 mm with a web thickness of 50 to 300 microns [11]. Shrinkage is typically on the order of 30 to 70% by volume; this can be advantageous when fine geometric features are desired that would otherwise would be difficult or expensive to fabricate [2]. While the use of interchangeable extrusion dies provides the opportunity to create an infinite variety of honeycomb shapes (i.e., [12]), it limits the macrostructure to planar geometry (due to the linear extrusions). This is a significant limitation of this manufacturing process as it does not offer designer control over the part macrostructure

1.2.2. *Additive Manufacturing of Cellular Materials*

Layer-based additive manufacturing processes (AM) offer the utmost geometrical freedom in the design and manufacturing of a part. As such, some researchers have looked into using AM techniques for the production of cellular materials. Indirect approaches (i.e., using AM to create patterns for casting) limit cell and truss size, constrain cell topologies, and are plagued by porosity due to the inability of the fluid to access all parts of the truss structure [13-15]. While direct creation of cellular materials through AM techniques eliminates all constraints on mesostructure design, the processes are constrained by the limited working materials available to conventional additive manufacturing techniques [16-18].

Quite a few commercially available metal-based AM processes exist. During a previous preliminary selection exercise, the authors concluded that the available metal-based AM techniques do not offer a feasible means of producing cellular materials since they suffer from several technical limitations [19]:

1. *Poor Resolution* – many of the technologies' depositions are too large to make the thin walls necessary to create cellular materials
2. *Limited Material Selection* – many of the techniques can deposit only certain types of metals (e.g., steel alloys); furthermore, most of the techniques are only capable of making parts of a proprietary material
3. *Poor Surface Finish*: due to the layer-by-layer deposition process, surface finishes of parts created by AM suffer from rough external features ("stair-stepping"); furthermore, poor surface finish results from the use of powders and warping effects from the use of high-powered lasers. Poor surface finish limits a process's ability to create small features for cellular materials. It also worsens its ability to efficiently pass fluids, thus increasing the pressure drop across the structure - important considerations for heat exchangers.

4. *Poor Material Properties*: metallic parts created by AM typically feature material properties that do not closely match their traditionally manufactured counterparts. Layered manufacturing also usually results in parts with anisotropic properties.
5. *Support Removal*: un-patterned material, or dedicated support material, can be trapped or be extremely difficult to remove in extremely complex internal geometry (i.e., microchannels found in cellular honeycombs).

A summary of the working principles and associated limitations of metal-based AM techniques is offered in Table 2.

Table 2. Limitations of Metal Solid Layer-Based Additive Manufacturing Techniques

Name	*Working Principle*	*Limitations*	*References*
Selective Laser Sintering (SLS)	Uses a CO_2 laser to selectively fuse polymer-coated metallic powder (stored in a bed) one layer at a time. Requires debinding, sintering, and infiltration	# 2 – 5	[20], [21], [22]
Direct Metal Laser Sintering (DMLS)	Similar to SLS, DMLS patterns energy in a powder bed. DMLS directly sinters a two-phase metallic powder system. Requires infiltration.	# 2 – 5	[23], [24], [25], [26], [27]
Selective Laser Melting (SLM)	Selectively melts metallic powder with an infrared laser. Does not require additional post-processing. Can make extremely small features.	# 3, 5	[28], [29]
Electron Beam Melting (EBM)	Uses a 4.8 kW electron beam to selectively scan and melt layers of metal powder	# 3, 5	[30], [31]
3D Printing (3DP)	Use of a printer head to print binder polymer over a metal powder bed. Requires sintering and infiltration.	# 3 – 5	[26]
Multiphase Jet Solidification (MJS)	A metal powder-binder mixture is extruded through a heated nozzle to create layers. Requires debinding, sintering, and infiltration	# 1, 3 - 5	[32], [33]
Laser Engineered Net Shaping Techniques (LENS)	Melting powdered metals with a high-powered Nd:YAG laser. Metal powder is fed into laser beam by nozzle. Direct Metal Deposition (DMD)	# 1, 3	[34], [35], [36], [37], [38]
Shape Deposition Manufacturing (SDM)	Combination of laser cladding (LENS process) with subtractive machining	# 1, 5	[39]
Ultrasonic Object Consolidation (UOC)	Solid-state joining techniques deposit layers of tape to form solid aluminum parts, followed by trimming step	# 2, 4, 5	[40]
Layered Object Manufacturing (LOM)	Selectively cuts stacks of sheet metal and fuses the layers together	# 3 - 5	[41]

1.3. Context: Designing a Cellular Material Manufacturing Process

The opportunity to improve the design of existing products and the ability to reap the full benefits of cellular materials in new applications drives the authors' exploration of a manufacturing process that provides a designer the freedom to dictate the morphology of the voids, the topology of the mesostructure, the overall geometry of the part, and the type of material to be used. The main over-arching limitation with all currently available cellular manufacturing methods is the lack of flexibility offered to a designer because of the imposed process constraints (Table 1). Even those methods that offer the ability to design the part mesostructure (Section 1.2) do not provide a designer the opportunity to fully specify the part macrostructure or material.

In an effort to create a cellular material manufacturing process that maximizes designer freedom, the authors look to the combination of the linear cellular honeycomb process and additive manufacturing. Specifically, the authors look to *the layer-based additive fabrication of metal oxide powders followed by post-processing in a reducing atmosphere as a means of fabricating three-dimensional, low-density cellular metal parts with designed mesostructure*.

In this paper, the authors begin working towards this goal through the conceptual design of a process chain that entails the additive fabrication of metal oxide powders for the realization of metal parts of designed mesostructure. Following the methodology as outlined by Pahl and Beitz [42], the design process begins with developing clarifying the design task (Section 2). Working principles are generated in Section 3, and then selected based upon their ability to meet the identified requirements (Section 4). Closure is offered in Section 5.

2. CLARIFICATION OF THE DESIGN TASK

The combination of the best traits of additive manufacturing and reduction of metallic oxide powders is a very promising solution to the limitations of existing cellular material manufacturing techniques. The capability of AM to selectively place material throughout a part alleviates the macrostructure limitations found in the metal oxide reduction process. Conversely, the extensive material selection and excellent material properties found in the metal oxide reduction technique ([11]) are a perfect complement to the material troubles found in traditional AM processes and the (post-) processing issues found in metal-based AM technologies.

In addition to these benefits, the simple use of metal oxide powders provides many advantages. The cost differential between a metal oxide powder and its metal counterpart is usually better than a 1-to-10 ratio [2]. Also, fine oxide powders are readily available in a pure and stable form. Compared to pure metal powders, metal oxides are safer as they are neither carcinogenic nor explosive.

The combination of these processes is feasible. The forming of metal oxide powders to create metal artifacts through reduction is not only limited to extrusion; the inventors of the process note that other forming methods are suitable, including slurry coating of sacrificial cores, slurry casting methods (slip, pressure, centrifugal, tape, and gel casting), and dry pressing [10]. The infusion of AM into the existing process chain adds opportunities for strategic material placement, custom macrostructure, and even functionally graded materials. Furthermore, other successful examples of such combination exist, such as the slurry-based 3D Printing of a tungsten carbide mixture with post-processing in a reducing atmosphere to create tungsten carbide-cobalt [43].

Table 3. Requirements List for Process for the Manufacture of Parts of Designed Mesostructure

D / W	*Requirement*
	Geometry
D	Able to process any macrostructure geometry
D	Able to process complex geometry (overhangs & internal voids)
D	Able to process small cell sizes (0.5 – 2 mm)
D	Build small wall thickness (50 – 300 μm)
W	Minimize amount of effort required to adapt to a new material
	Material
D	Able to process multiple materials (steel, iron, chromium, aluminum, titanium, copper, etc.)
W	Able to process standard working material (i.e., material is not proprietary)
	Production
W	Maximize deposition rate ($\geq$ 10 cm^3/hr)
D	Build envelope is 250 x 250 x 250 mm or larger
W	Does not require additional post-processing
	Quality Control
D	Parts are $\geq$ 98% dense
D	Material properties are comparable to standard
D	Minimize surface roughness before finishing ($\leq$ 0.02 mm Ra)
D	Maximize accuracy ($\geq$ +/- 0.05mm)
D	Minimize z-resolution ($\leq$ 0.1 mm)
	Operation
W	Does not require special operating environment
W	Minimize operator interaction
	Recycling
D	Minimize environmental impact by minimizing wasted material
W	Reusable wasted material
	Costs
D	Minimize cost of technology
D	Minimize cost of maintenance
W	Minimize cost of material
W	Easily scaled for large applications

2.1 The Manufacturing Process Requirements

With the general design task outlined, a list is created to quantify design requirements and to further clarify the design task. See Table 3. Demands (D) are requirements that must be met before a given design may be accepted. Requirements that are wishes (W) need to be considered whenever possible unless their satisfaction compromises demands or more important requirements. The manner in which various concepts fulfill the requirements will influence the evaluation process (Section 4).

3. CONCEPTUAL DESIGN OF AN ADDITIVE MANUFACTURING PROCESS

3.1 The Structure of Additive Manufacturing Functions

Although there are many different types of AM technologies, each has the same end goal: the manufacturing of a part through the successive deposition/forming of material, one layer at a time. From an abstract view, each AM process follows the same five functions:

(i) *store material* – each AM technology relies on a starting material that will be consolidated to form the final part (e.g., powder, tape, resin, slurry, etc.)

(ii) *pattern* – the process can involve patterning material to directly deposit material by scanning each layer. Alternatively, the process can selectively pattern energy in order to transform the material into the finished part. Finally, the process can pattern both the material and energy simultaneously.
(iii) *provide energy* – each AM technology requires the input of some form of energy in order to transform, shape, or change the phase of the raw material to obtain the desired part
(iv) *provide new material* – each AM technology must have a method of supplying material for each layer. While some technologies directly deposit material, most use a recoating process to prepare for additional layers.
(v) *provide support* – many AM technologies have a method of supporting deposited material to ensure stability, and to be able to build complex geometry such as overhangs.

The resulting function structure (Figure 3) provides a framework for the ideation of potential working principles.

3.2 Working Principles for the Additive Manufacturing of Parts with Designed Mesostructure

In this section, individual concepts for each processing function are combined via a morphological matrix [44] in order to develop working principles. In [19], the authors observed that certain embodiments of these functions prevented AM technologies from being a feasible solution for the manufacture of cellular materials. Specifically, the use of a powder bed (an embodiment of the "Provide Support" function) prevents the processing of extremely complex internal geometry (i.e., microchannels found in cellular honeycombs) since un-patterned material cannot be removed. It was also determined that those technologies that rely on patterning in one dimension are significantly limited due to the physical limit on the scanning speed of an AM machine. This limits the economic competitiveness of AM technologies compared to traditional manufacturing technologies. Furthermore, when a requirement for small features exists, as it does with cellular material manufacturing, the act of patterning with small-width one-dimensional scans becomes even more limiting. As they have direct relation to the requirements listed in Table 3, these limitations are kept in mind as working principles are generated.

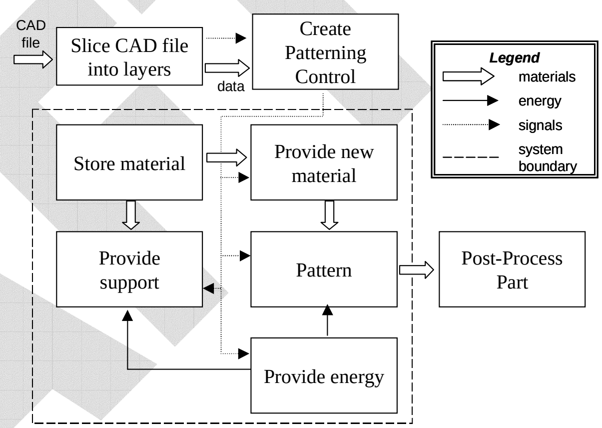


Figure 3. Additive Manufacturing Function Structure

3.2.1 One-Dimensional Patterning

<u>*Selective Laser Sintering*</u>

Ceramic parts are created with SLS through solid state sintering (SSS) – a bed of ceramic powder is heated to a temperature close to its solid state sintering temperature; additional energy is provided by a high-powered laser to initiate diffusion and neck formation between the particles (Figure 4). A wide variety of materials can be processed with SSS, but the process is slow and a post-sintering operation is required to improve part characteristics [18]. Phenix Systems commercialized an SLS-like system that realizes ceramic parts through SSS. Parts with accuracy of +/- 50 μm (per 120 mm) and a minimum feature size of 300 μm have been reported using this process [45].

Liquid phase sintering (LPS) involves the coating of the ceramic particles with a binder material (or the ceramic particles are simply mixed with binder particles). The laser's energy melts the binder and thus joins the particles. LPS is more favorable for the proposed manufacturing process chain than SSS since it produces a green part suitable for post-processing in a reducing atmosphere.

While SLS provides opportunities for processing several different ceramic materials and functionally graded parts, the main drawback of the technique resides in the inherent high level of residual porosity that requires a post treatment such as re-sintering or infiltration [46]. The surface finish obtained is sensibly rougher compared to parts obtained by powder compaction, and surface finishing (only possible on accessible surfaces) is necessary [47]. As such, ceramic SLS is typically only used for the creation of molds for the indirect production of ceramic parts [48].

Another drawback of this technology is the manner in which it patterns energy in only one dimension. In order to alleviate this limitation, another possible embodiment of this technology is presented in Figure 4. This principle uses a high-powered lamp to selectively perform LPS (through masking) on the top layer of a slurry mixture of ceramic and a binder. The use of a mask/lamp system improves the speed of this technology by allowing it to pattern a two-dimensional material area without time-consuming raster scanning [49]. Working with such a suspension, the difficulties associated with heat-affected zones that are found in the sintering powders could be reduced [50]. Unfortunately, the reliance on a powder bed prevents this technology from processing cellular materials with closed cells or small channels due to the inability to sufficiently remove un-sintered material.

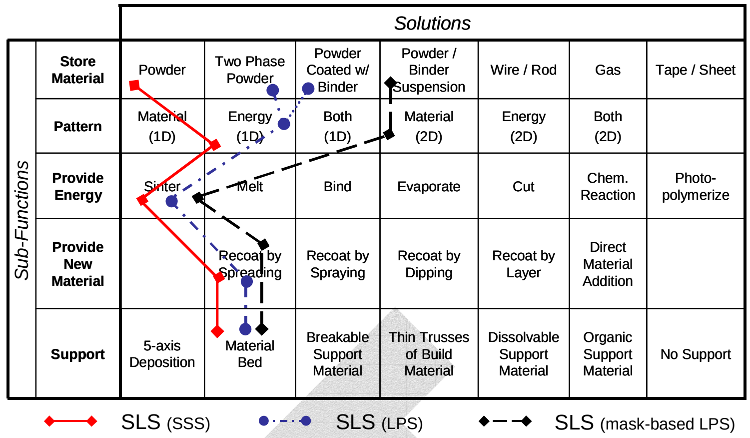


Figure 4. Selective Laser Sintering Morphological Matrix

Stereolithography

Stereolithography (SLA) involves the use of an ultra-violet (UV) laser to selectively cure a photopolymer resin (Figure 5). To create ceramic parts via this technology, fine-grained ceramic particles are combined with a monomer and photoinitiators to create a modified photopolymer resin which is then cured in an unmodified SLA machine. Researchers have been able to achieve up to 67% volume loading with ceramic particles [51]. After the green part (approximately 50% ceramic and 50% UV-polymerized binder [52]) is made by selective curing with the UV laser, the part is sintered at high temperatures. Parts typically undergo ~15% linear shrinkage; results have given densities as high as 96% theoretical density [53]. Unfortunately, some cracking and delamination during sintering has been observed [52].

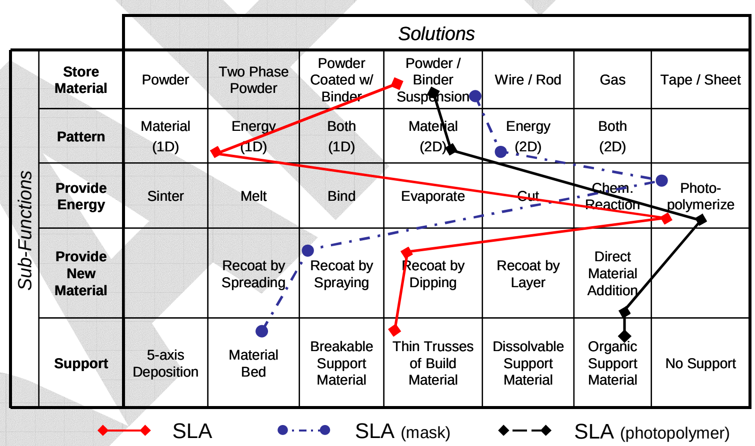


Figure 5. Stereolithography Morphological Matrix

In an effort to obtain smaller feature sizes, researchers have explored the modification of the technology to make ceramic microstructures with the use of micro-SLA systems. These techniques employ the use of masks (created by a digital-micro mirror display) to deliver 1-2µm spots of UV light onto the resin vat [54,55]. This embodiment successfully reduces the cost (i.e., it doesn't require a UV laser) and time (entire layers of the suspension are cured simultaneously) of the SLA concept.

Another embodiment of the photopolymerization concept is the inkjet printing of UV resins. The curing of individual droplets of UV resin provides drop-by-drop control over material deposition. Since arrays of printing nozzles can be used, this embodiment is capable of patterning material in two-dimensions. Unfortunately, the requirement on suspension viscosity (enforced for successful deposition) severely limits the solids loading [56].

While SLA ceramic parts benefit from the process's high resolution, good surface finish, and high-density green parts, the process suffers from several limitations. The main flaw stems from its inability to process multiple types of ceramics. Most ceramics prevent the UV radiation from being absorbed at a great enough depth (150-200 µm) to achieve curing and binding between layers. This problem is exacerbated by the need to have a high-solids loading in the suspension [57]. Due to this limitation, only three ceramics have been successfully created using SLA: alumina (Al_2O_3), silica (SiO_2), and PZT [57,53]. Many researchers have attempted silicon nitride, but the cure depth was too small [58,59]. An additional problem with the SLA concept is that the viscous resin prevents the creation of cellular structures with extremely small microchannels or honeycombs. While the paste would be viscous enough to support overhanging structure, it would be extremely difficult to remove the uncured resin from the channels.

Fused Deposition of Ceramics

In ceramic Fused Deposition Modeling (known as Fused Deposition of Ceramics, FDC), filaments comprised of ceramic particles in thermoplastic binders (50-65 vol. %) are extruded through a nozzle (typically 250-500 µm in diameter). The material is heated as it is extruded, thus melting the binder to provide suitable viscosity. As the molten binder contacts previously deposited layers, it partially remelts and promotes strong bonding of the layers (Figure 6). After the green part is formed, the binder is burned out, and the part is sintered to its final density (typically 98% with 18% linear shrinkage). Since green FDC parts are similar to injection molded green ceramic parts (both require post processing such as binder removal and densification) many ceramics have been successfully deposited with FDC (e.g., silicon nitride, silica, alumina, and lead-zirconium titanate) [60]. FDC also benefits from direct material addition and the use of a separate support material that can be dissolved in a water bath.

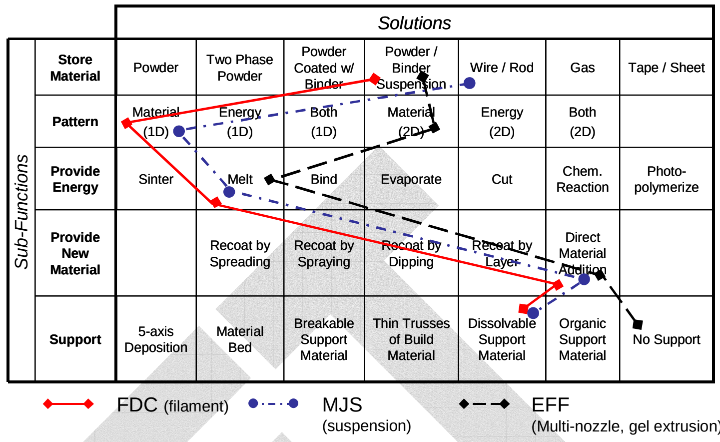


Figure 6. One Dimensional Extrusion-based AM Morphological Matrix

Some limitations accompany the FDC process. First, deposits of the FDC machine are larger than other SFF approaches; due to material flow, the width of deposit is usually 1.2 to 1.5 times the diameter of the nozzle (~0.75 mm) [61]. Porosity plagues most parts made with FDC due to poor optimization of material flow, filament/roller slippage, liquefier head motion (start-stop motion), and build/fill strategies. FDC parts also suffer from poor surface finish. Large layer thicknesses (~0.5 mm) provide a stair-stepping effect for curvature in the z-direction. Although most surface defects can be eliminated by post-processing, internal defects result in strength limitation which cannot be eliminated after part fabrication [61]. Finally, there are often density gradients in the filament; thus depositions can be non-homogeneous throughout the part [62].

Other embodiments of this extrusion-based approach to freeforming ceramics include multi-phase jet solidification (MJS) [63] [64], extrusion freeforming (EFF) [65], and contour crafting (CC) [66]. These technologies are capable of extruding more viscous solutions (since they extrude a powder-binder mixture or liquefied substance instead of feedstock). In an effort to improve the minimum feature size capable of extrusion, Grida and Evans have modified existing EFF technology to extrude thin fibers (> 100 µm) of ceramic suspensions through hypodermic needles. The authors were unable, however, to extrude thinner fibers since they would solidify before contacting the previously deposited layers [67]. In order to increase the deposition rate of the process, one could visualize an array of deposition heads to enable parallel scan lines, thus patterning successfully in two dimensions. The selective extrusion of ceramic gelcasting suspensions is also a promising research direction [68]. Support structures for overhangs are is not needed if the slurry sets immediately upon extrusion [69]. Despite these improvements, these technologies suffer from the same internal defects encountered with FDC.

3.2.2 Two-Dimensional Patterning

Three-dimensional Printing

Three-dimensional printing (3DP) of ceramics involves the selective printing of a binder over a bed of ceramic powder [70]. Green parts created by this process are subjected to a thermal decomposition prior to sintering to remove the polymer binder (Figure 7, following page). Alumina, silica, and titanium dioxide have been made with this process [71]. Research involving the 3DP of ceramics encountered early setbacks because of the use of dry ceramic powders. The fine powders needed for good powder bed density did not generally flow well enough to spread into defect-free layers [70]. Furthermore, since green part density was inadequate with the use of dry powders, isostatic pressing was implemented after the printing process. This extraneous requirement severely limits the types of macrostructure capable of being processed.

To counteract the problems encountered with recoating a dry powder bed, research on ceramic 3DP has shifted to the use of a slurry-based working material. In this approach, layers are first deposited by ink-jet printing a layer of slurry over the build area. Once the slurry is dried, binder is selectively printed to define the part shape. This is repeated for each individual layer, increasing build time dramatically. Multiple jets containing different material composition or concentration could be employed to prepare components with composition and density variation on a fine scale (100 µm) (thus the 2D patterning distinction) [72]. Alumina, and silicon nitride have been processed with this technique, improving green part density to 67%, and utilizing layer thicknesses as small as 10 µm [73]. Kernan and coauthors report good dimensional control (within one binder droplet diameter) and a final part density comparable to the equivalent conventionally processed material with this process; however, binder print-through on the bottom surfaces resulted in a poor surface finish [43].

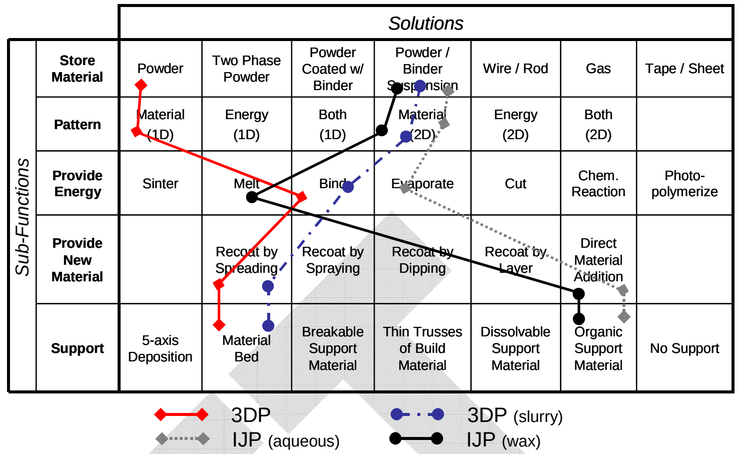


Figure 7. Printing Morphological Matrix

The main limitation of slurry-based 3DP is its reliance on a powder bed. While the powder bed provides ample support for the part during construction, it also makes part retrieval very difficult. Moon and coauthors note that the requirement of high bed packing density opposes the requirement of efficient separation of the part from the unpatterned material [74]. In the context of creating cellular materials, this is a very large limitation as it may prove to be impossible to successfully remove the unprinted slurry from microchannels and other internal features.

Ink-Jet Printing

Inkjet printing is an AM technique that relies on the selective deposition of individual droplets of material to create a solid part (Figure 7). Research of direct inkjet printing of ceramics has presented two different material processing embodiments. The first, inkjet printing of ceramic inks, involves the selective deposition of ceramic powders in a well-dispersed aqueous suspension [75]. In order to successfully deposit the mixture through the printer's 30-120µm nozzles, the suspension must be very dilute (typically only containing 5-14% volume ceramic). Once deposited, the mixture is then dried by a hot-air blower (up to 20 seconds) in order to assist in the evaporation of the solvent [76]. Green parts created by this process (i.e., dried ink) typically have a volume fraction of 0.63. After sintering, final part density is 98% and endures a 20% linear shrinkage. Due to the low solids content of the deposition, a single pass makes a deposit of only up to 0.7µm [76]. Besides being extremely slow, jetting of aqueous ceramic suspensions also suffer from sedimentation during the build; as such, the nozzles must be flushed of ink every 50-100 passes.

The crux of hot-melt inkjet printing is the deposition of melted droplets of ceramic-wax suspensions that solidify upon impact cooling [77]. Hot-melt printing is much faster than aqueous printing because it does not require drying after each pass, and the deposits have significant thickness (thus requiring fewer patterning passes). Unfortunately, due to viscosity limitations, the volume loading of the suspension is constrained to 30-40% volume ceramic. As a result, the final sintered object undergoes a 20% linear shrinkage and a final relative density of 80% [78].

Overall, direct ink jet printing is capable of producing very small features (75 µm droplets and minimum features < 100 µm) [77]. The process's individually controlled nozzles present opportunities for changing the part composition from point-to-point, thus producing graded materials throughout the entire part efficiently [79]. Furthermore, the array of deposition nozzles found in this technology provides an efficient manner for patterning; current embodiments have 500 nozzles that print 70 mm across, thus eliminating the need for an x-stage [80]. The one foreseeable limitation with a direct-deposit method such as ink-jet printing is the requirement for support structures for overhanging material. Mott et al., have attempted to address this issue through the simultaneous deposition of a carbon suspension as a fugitive mechanical support [81].

Layered Material Approaches

There are two working principles that are centered in patterning entire layers of material at time: the Metal Printing Process (MPP), and Layered Object Manufacturing (LOM) (Figure 8).

MPP is centered on photo-masking and electrostatic attraction to print ceramic (or metal) powders similar to high-speed photocopiers [82]. The printed layers are then sintered via either electric contact sintering or microwave sintering. Conceptually, this principle offers many advantages (direct material addition, 2D material patterning); however, potential problems include the porosity of printed part, the quality of adherence of the support powder to the build powder, and dealing with non-conduction powders (such as ceramics).

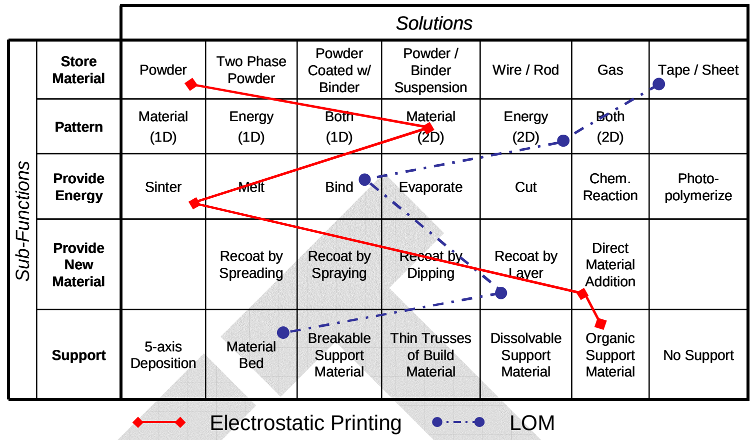


Figure 8. Morphological Matrix for Layered Object Manufacturing and Electrostatic Printing

LOM selectively cuts commercially available green ceramic tape layers and binds them together in order to create the final part [83]. Although this ability to process entire layers is attractive, LOM parts suffer from density gradients, delamination, and anisotropic material properties [84,85] . While the excess material cut from the part provides support during the process, it is impossible to retrieve this material from internal voids. Even CAM-LEM's "cut-and-stack" approach [86] proves to be troublesome for the complex cross-sections of cellular materials.

4. PRELIMINARY SELECTION OF WORKING PRINCIPLES

With the technologies to be evaluated identified, a preliminary selection process is employed to identify those concepts that are most likely to satisfy the requirements identified in Section 3.1. Due to the lack of sufficient quantitative engineering data presented for each alternative, it is not possible to proceed with a full engineering selection process. Mistree and coauthors propose the Preliminary Selection Decision Support Problem (DSP), a technique for making selections in a complex, multi-faceted design environment [87]. The Preliminary Selection DSP provides a designer a framework in which most-likely-to-succeed concepts can be identified through the systematic comparison of alternatives based upon soft engineering data.

To begin the preliminary selection process, selection criteria must be developed around the requirements listed in Table 3. As such, each concept will be

Table 4. Preliminary Selection Criteria

Category / Criteria	*Description*
Economics	
Technology Cost	The cost of purchasing and operating the technology. Prefer low cost (i.e., laser-less technologies)
Time	
Deposition Rate	The amount of volume deposited per unit time. Prefer high rate (> 10 cm^3/hr)
Performance	
Minimum Feature Size	The smallest feature able to be produced by technology. Prefer small size; wall thicknesses 50-300 μm.
Complex Geometry	The ability of the technology to create complex geometry. Preference goes to those technologies that can produce overhangs and small channels and allow efficient part retrieval & cleaning.
Surface Finish	Quality of surface able to be produced by machine. Since this data is not quantitatively offered in the literature, this is also interpreted as a function of z-resolution. Prefer small surface roughness < 0.02 mm Ra and a z-resoultion < 0.1 mm.
Materials	
Green Part Solids Loading	To improve sintering characteristics it is preferred that the green part has a large amount of solids loading.
Material Properties	Quality of materials produced by technology. Preference goes to those technologies that are capable of producing materials that are close to standard values and do not display anisotropic qualities.
Material Selection	The number of metallic materials able to be processed by the technology. Prefer technologies that can process multiple materials and commercially available materials.

evaluated by the criteria outlined in Table 4. This list represents criteria that are specific to manufacturing parts of all classes (low cost, high throughput, multiple materials, good material properties), as well as criteria that are specific to manufacturing parts of designed mesostructure (extremely small features, excellent surface finish, and complex geometries).

The Preliminary Selection DSP technique involves a series of comparisons between each working principle alternative and a chosen datum in the context of the different selection criteria. The concepts are evaluated against the datum as inferior (-1), equal (0), or superior (+1). Since the comparisons are based upon soft engineering data, this three-point scale is appropriate; at this point in the design process a designer can only identify that one concept is preferred over another, but cannot quantitatively identify by how much the concept is preferred. It is noted that value assessments are subjective and experience-based; however, this is not a shortcoming – evaluation procedures are meant to enhance an engineer's decision making ability. The scores are then summed and normalized within each category. Ranks are assigned based on the summed score of all the normalized scores of each criterion. A sample comparison matrix, wherein SLA is the chosen datum, is given in Table 5.

Table 5. Comparison Matrix for Stereolithography Datum

	SLS	SLA	MJS	EFF	3DP	IJP-a	IJP-w	EP	LOM
ECONOMICS									
Technology Cost	0	0	1	1	1	1	1	1	1
Score	0	0	1	1	1	1	1	1	1
Normalized Score	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
TIME									
Deposition rate	1	0	-1	-1	-1	-1	1	1	1
Score	1	0	-1	-1	-1	-1	1	1	1
Normalized Score	1.00	0.50	0.00	0.00	0.00	0.00	1.00	1.00	1.00
PERFORMANCE									
min. feature size	-1	0	-1	-1	-1	-1	-1	-1	-1
complex geometry	0	0	1	1	0	1	1	1	-1
surface finish	-1	0	-1	-1	-1	0	0	-1	-1
Score	-2	0	-1	-1	-2	0	0	-1	-3
Normalized Score	0.33	1.00	0.67	0.67	0.33	1.00	1.00	0.67	0.00
MATERIALS									
Solids Loading	-1	0	0	0	1	1	-1	0	1
Material properties	-1	0	-1	-1	1	1	0	-1	-1
Material selection	1	0	1	1	1	1	1	1	1
Score	-1	0	0	0	3	3	0	0	1
Normalized Score	0.00	0.25	0.25	0.25	1.00	1.00	0.25	0.25	0.50
OVERALL SCORE									
Sum of Scores	1.33	1.75	1.92	1.92	2.33	3.00	3.25	2.92	2.50
Rank	9	8	6	6	5	2	1	3	4

Multiple weighting schemes are employed in the Preliminary Selection DSP to address the interaction of the selection criteria. The weighting schemas for each scenario are presented in Table 6. The first three scenarios represent increasing importance placed on the technology's ability to create the geometry common in cellular materials out of multiple materials. The fourth scenario represents a case wherein importance is placed on the speed and cost of the process.

Table 6. Weighting Scheme Scenarios

Criteria	*One*	*Two*	*Three*	*Four*
Economics	0.2	0.1	0.15	0.35
Time	0.2	0.1	0.2	0.35
Geometry	0.3	0.4	0.4	0.15
Materials	0.3	0.4	0.25	0.15

Normalized scores for each concept are computed by multiplying the normalized score of each concept's attribute category (Table 5) by the weighting values (Table 6). The summed score serves as the merit function for each generalized concept. The results from the SLA datum are graphically shown in Figure 10.

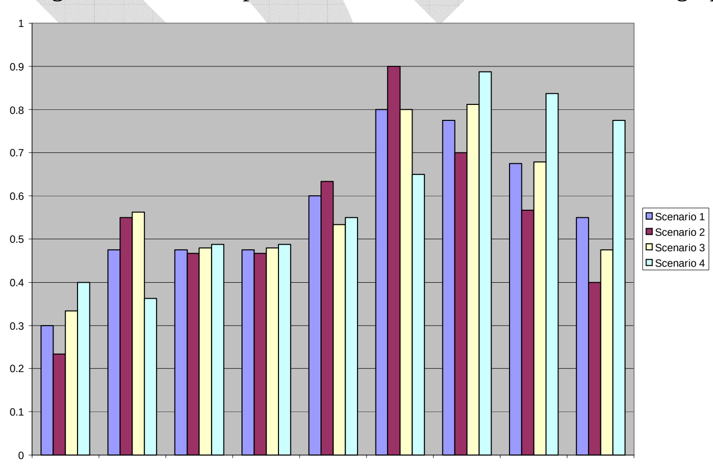


Table 7. Ranking of Concepts for the SLA Datum

	Scenario Number			
Alternative	One	Two	Three	Four
SLS	9	9	9	8
SLA	6	5	4	9
MJS	6	6	6	6
EFF	6	6	6	6
3DP	4	3	5	5
IJP-a	1	1	2	4
IJP-w	2	2	1	1
EP	3	4	3	2
LOM	5	8	8	3

Figure 10. Evaluated Merit Functions for the SLA Datum

Each alternative is ranked from the merit function values. Ranking results for the SLA datum are shown in Table 7. Ink jet printing, electrostatic printing, and three-dimensional printing are identified as the most likely to succeed technologies for the scenarios when SLA is set as the datum.

This step is repeated in a similar manner using multiple datums for all weighting scenarios in order to dispel any prejudice. Once the comparison process is repeated for multiple datums, the average overall merit function for each of the alternatives for all weighting scenarios is calculated. These results are shown in Table 8. Rank ordering these values results in a list of most likely to succeed technologies, as presented in Table 9.

Table 8. Overall Merit Function for Preliminary Selection

	Scenario Number			
Alternative	One	Two	Three	Four
SLS	0.200	0.121	0.208	0.319
SLA	0.500	0.563	0.571	0.406
MJS	0.494	0.408	0.436	0.622
EFF	0.548	0.501	0.521	0.618
3DP	0.415	0.470	0.370	0.333
IJP-a	0.800	0.900	0.800	0.650
IJP-w	0.765	0.708	0.778	0.851
EP	0.489	0.339	0.452	0.713
LOM	0.458	0.402	0.410	0.541
	Overall Merit Function			

Table 9. Overall Rankings for the Most Likely to Succeed Concepts

	Scenario Number			
Alternative	One	Two	Three	Four
SLS	9	9	9	9
SLA	4	3	3	7
MJS	5	6	6	4
EFF	3	4	4	5
3DP	8	5	8	8
IJP-a	1	1	1	3
IJP-w	2	2	2	1
EP	6	8	5	2
LOM	7	7	7	6
	Rank			

From the rankings it is observed that ink jet printing (IJP-a and IJP-w) and extrusion freeform fabrication (EFF) are the most likely to succeed technologies. These technologies were consistently preferred because of their capability to process multiple materials and to create small features, functionally graded materials, and intricate geometry. The solution of the preliminary selection DSP has proven to be a sufficient method for the authors to examine methodically the tradeoffs found in the analysis of the generated working principles.

5. CLOSURE

In this paper the authors detail the conceptual design of a manufacturing process for the realization of parts of metal cellular materials with designed mesostructure. Since existing cellular material manufacturing and metal-based additive manufacturing (AM) techniques do not provide a designer to specify material composition, mesostructure, or part macrostructure, the authors look towards the layer-based additive fabrication of metal oxide powders followed by post-processing in a reducing atmosphere as a means of achieving this goal.

By following a systematic design method, the authors identify fundamental limitations of existing AM embodiments and the key requirements of the to-be-designed manufacturing process (Section 2), which assist in the generation of working principles (Section 3). The formulation and solution of a Preliminary Selection Decision Support Problem provides a framework for the authors to select amongst the working principles despite having only soft engineering data. As a result of this systematic conceptual design approach, three working principles are determined to be worthy of further investigation and embodiment: ink jet printing of aqueous ceramic suspensions, hot-melt printing of wax-based ceramic suspensions, and extrusion of either wax, colloidal, or gel ceramic suspensions. From this process, the authors look to performing feasibility experiments in order to obtain "hard" engineering data sufficient for a quantitative selection process.

A high-level contribution found throughout this paper is the recording of a systematic design process of an additive manufacturing technology. While the development of existing AM processes was typically a due to the discovery of a specific embodiment of the "pattern" function (thus, a "technology push"), the authors' design endeavor is driven by the creation of a specific class of geometry (or, an "application pull"). From this perspective, learning opportunities arise from the systematic analysis of the characteristics of the principal solutions of Additive Manufacturing.

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